Efficient Water Allocation with Win-Win Conservation Surcharges: The Case of the Ko'olau Watershed

Brooks A. Kaiser[1], Wetinee Matsathit[2], Basharat A. Pitafi[2], and James A. Roumasset[2]

Abstract

This paper revisits the problem of an underpriced and overexploited groundwater resource. Like other renewable resources, an aquifer replenishes itself over time via recharge from rain percolation. Not only is the aquifer vulnerable to simple overdrafting, but recharge quantities are also determined by forest quality. Healthy multi-tiered forests hold more water in place to increase recharge than bare soil with a single canopied forest cover. Forest quality therefore affects water quantity, and decisions regarding forest conservation expenditures must incorporate this physical relationship, as well as the economic usage of the groundwater resource. In this paper, we provide an analytical framework for evaluating the groundwater benefits of watershed conservation when without such conservation damage to the watershed occurs and brings about partial recharge loss. We consider both the case of a certain and immediate loss and the case of a probable and future loss. We illustrate the framework for the case of the Pearl Harbor aquifer on Oahu where we estimate the benefits of both conservation and improved water management and contrast these with the benefits of efficiency pricing without conservation.

[1] Dept. of Economics, Gettysburg College, Gettysburg, PA, 17325.
[2] Dept. of Economics, University of Hawaii, Honolulu, HI 96822.

1. Introduction

This paper revisits the problem of an underpriced and overexploited groundwater resource. Like other renewable resources, an aquifer replenishes itself over time via recharge from rain percolation. Underpricing, population growth and income growth result in excessive overdrafting and premature desalination.

Not only is the aquifer vulnerable to simple overdrafting, but the parameters of recharge quantities are also determined by forest quality. Healthy multi-tiered forests hold more water in place to increase recharge than bare soil with a single canopied forest cover. Forest quality therefore affects water quantity, and decisions regarding forest conservation expenditures must incorporate this physical relationship, as well as the economic usage of the groundwater resource. An under-conserved watershed resource decreases the amount of water inflow to the aquifer. Groundwater management and watershed conservation are therefore interdependent problems.

The management problem is rendered even more difficult because conservation expenditures are intended to reduce the risk of watershed degradation. Insufficient conservation spending deteriorates the forest quality. Watershed degradation, in turn, reduces the amount of water recharge to the aquifer. This process can happen at any time in the future. Our state variable, i.e. the groundwater resource, depends on another state variable, watershed quality, which is subject to random attacks. Technical difficulty in economic modeling and data constraints limit our analysis to a dichotomous probability distribution of the adverse event. In a finite time, with a given probability, a sudden attack instigated by human activity but propagated by nature deteriorates the forest quality and decreases water released to the aquifer. In what follows, we provide an analytical framework for evaluating the groundwater benefits of watershed conservation. In short, this requires optimizing inter-temporal groundwater extraction in the face of uncertainty, with and without conservation expenditures. The increase in the expected present value of the aquifer is a benefit of conservation.

We illustrate the framework for case of the Pearl Harbor aquifer on Oahu. Inasmuch as current groundwater is under-priced, the benefits of conservation would be largely wasted without commensurate reforms in water pricing. Accordingly, we estimate the benefits of both conservation and improved water management and contrast these with the benefits of efficiency pricing without conservation. We show that moving to a system of efficiency pricing with conservation surcharges is a win-win-win solution for water consumers, taxpayers, and the environment.

In the next section, we discuss a hydrologic-economic model under uncertainty and briefly explain the optimal conditions for water extraction. Watershed conservation is incorporated as a policy instrument. Section 3 illustrates the effects of watershed conservation on scarcity rent and the rate of water extraction via the case of Pearl Harbor aquifer. The final section highlights the nature of the optimal solution and underscores the case for conservation and water-policy reform.

2. Model

Following Krulce *et. al.* (1997), the regional hydrologic-economic model is constructed to optimize groundwater use under uncertainty for the coastal aquifer given the hydrologic constraints, the costs of extraction and desalination, and the benefits of groundwater extraction. We solve for the efficient use of water by incorporating the concept of watershed management.

Benefits of water consumption are represented by consumer surplus area under a market demand curve. Costs of water consumption comprise of extraction cost and cost of the backstop technology, desalination. When cost of extracting water for wells surpasses desalination cost, desalination method is preferred as an alternative source of water supply.

Variations in head level capture the dynamics of the hydrological model of the aquifer. The aquifer receives recharge, whose magnitude varies with watershed quality. Changes in head level, and therefore storage, occur naturally as a function of recharge and leakage levels are anthropogenically affected by extraction rates. Extraction changes the natural equilibrium head level over time; extraction that is more rapid than net recharge will eventually deplete the aquifer. The aquifer head evolves over time as $\dot{h}_t = w - l(h_t) - q_t$.

Our problem involves a stock-dependent recharge and the stock is uncertain. The groundwater recharge depends on the state of the forest watershed that is subject to attacks from invasive species and animals. Pindyck (1984) assumes an additive stochastic component to a renewable's growth rate. Dasgupta and Heal (1979) model uncertainty about a non-renewable stock due to future discoveries, resource substitutions, and the cost of exploration. Tsur and Zemel (2002) have combined both types of uncertainty, albeit with the assumption that aquifer recharge, which depends on a habitat subject to random attack, becomes useless once and for all when the aquifer is attacked. Despite the fact that this drastically simplifies the problem, the resulting model is highly complex.

Inasmuch as our problem is more complex and our technical virtuosity less than that of Tsur and Zemel, we assume that the event either happens or does not at a fixed time in the future and that the event is associated with a known habitat damage and consequence for recharge. By abstracting from the actual situation wherein the habitat can be attacked every year, we are approximating a Markov chain involving small probabilities of small but possibly cumulative damages every year with a larger probability of something more damaging happening in 20 years. We assume that there is a 10% chance of damages to forest quality that will reduce water recharge to the aquifer by 30%. Once the event occurs, forest quality, and thus recharge, remains low due to the virtual irreversibility of successful biological invasions.

Hence, a hypothetical social planner chooses the extraction rate of water from the aquifer to maximize the present value of net social surplus.

$$\underset{q(t),\, b(t)}{\text{Max}} \int_0^{t_e} e^{-rt} \left(\int_0^{q} D^{-1}(x,t)dx - c^q(h(t))q(t) \right) dt +$$

$$p_{ne} \int_{t_e}^{\infty} e^{-rt} \left(\int_0^{q+b} D_{ne}^{-1}(x,t)dx - c^q(h(t))q(t) - c^b b(t) \right) dt +$$

$$p_e \int_{t_e}^{\infty} e^{-rt} \left(\int_0^{q+b} D_e^{-1}(x,t)dx - c^q(h(t))q(t) - c^b b(t) \right) dt$$

Subject to:

$$\dot{h} = \begin{cases} w - l(h(t)) - q(t), & 0 \le t \le t_e \\ w - l(h(t)) - q(t), & t > t_e \ \text{ \& no event (prob. } p_{ne}) \\ w_{low} - l(h(t)) - q(t), & t > t_e \ \text{ \& event (prob. } p_{ne}) \end{cases}$$

where:

r = discount rate

t = time from the benchmark period to the current period

$q(t)$ = groundwater quantity consumed at time t.

c^q = cost of extracting unit volume of water.

$b(t)$ = backstop quantity consumed at time t

c_b = unit cost of backstop technology production

x = integration index for the water quantity demanded

$D^{-1}(x, t)$ = inverse demand function: the price at time t

$h(t)$ = head level at time t in the aquifer.

w = constant recharge rate from watershed

$l(h(t))$ = leakage function: the leakage corresponding to the head level, $h(t)$

ρ_e = probability that at a definite time (t_e) an *adverse* event will happen.

ρ_{ne} = probability that at a definite time (t_e) an *adverse* event will not happen.

w_{low} = decreased water recharge due to an *adverse* event.

The study analyzes the optimization problem into two cases. Case 1 describes a special case wherein $t_e = t_0$ and $p_e = 1.00$. The adverse event is a certain case that happens in the current period. Watershed degradation decreases the constant recharge rate, w, by 31%. Case 2 demonstrates the analysis of watershed degradation as an uncertain future event with $p_e = 0.1$ and $t_e = 20$. In 20 years, there is 10% probability that watershed degradation will lead to the reduced recharge.

For Case 1: watershed as a certain event, the appropriate current value Hamiltonian and necessary conditions for an optimal solution can then be derived. The current value Hamiltonian for this problem is

$$\mathrm{H} = \int_0^{q+b} D^{-1}(x,t)\,dx - c^q(h_t)q\ \ (t) - c_b b(t) + \lambda_t\left[w - l - q(t)\right] \text{where } \lambda_t \geq 0$$

Following Kamien and Schwartz (section 8 and 10), the necessary conditions are

(1) $$\dot{h}_t = \frac{\partial H}{\partial \lambda_t} = w - l(h_t) - q_{t,}$$

(2) $$\dot{\lambda}_t = r\lambda_t - \frac{\partial H}{\partial h_t} = r\lambda_t + c'(h_t)q_t + l(h_t),$$

(3) $$\frac{\partial H}{\partial q_t} = D_t^{-1}(q_t + b_t) - c(h_t) - \lambda_t \leq 0 \quad \text{if} < \text{then } q_t = 0,$$

(4) $$\frac{\partial H}{\partial b_t} = D_t^{-1}(q_t + b_t) - \overline{p} \leq 0 \quad \text{if} < \text{then } b_t = 0.$$

To solve the system of equations, we define the optimal price path as $p_t \equiv D_t^{-1}(q_t + b_t)$. Assuming that the cost of desalination is high enough so that water is always extracted from the aquifer, condition (3) holds with equality and yields the *in situ* shadow price of water, as the royalty (i.e., price less unit extraction cost).

(5) $$\lambda_t = p_t - c(h_t)$$

By rearranging equation (2), arbitrage condition is defined as equation (6) below.

(6) $$p = c + \frac{\dot{p}}{r} - \frac{c'(h)q}{r} - \frac{\lambda l'(h)}{r}$$
$$\equiv c + MUC$$

This implies that at the margin, the benefit of extracting water must equal the total cost of extracting water, i.e., price equals to cost plus marginal user cost (MUC).

Rewriting equation (4) yields

(7) $p_t \le c^b$ if < then $b_t = 0$

Desalination will not be used if its cost is higher than the price of freshwater. When desalination is used, price must exactly equal the cost of the desalted water. (We can substitute $p_t = c^b$ into (5) to get $\lambda_t = c^b - c(h_t)$ whenever desalination is used). Taking this expression and its time derivative and combining these with equations (1) and (2) by eliminating $\lambda_t, \dot{\lambda}_t$, and $\dot{h}_t$, yields

(8) $$c^b - c(h_t) = -\frac{(w - l(h_t))c'(h_t)}{r + l'(h_t)}$$

Since $c' < 0, c'' \ge 0, w - l > 0, l' > 0,$ and $l'' \ge 0,$ the h that solves (8) is unique. Whenever desalination is being used, the aquifer head is maintained at this optimal level denoted as $h*$. At $h*$, water extracted from the aquifer equal the net inflow to the aquifer. That is $q_t = w - l(h*)$. Excess of quantity demanded is supplied by desalinated water at the price equals to c^b. Once desalination begins, from (7) $p_t = c^b \Rightarrow \dot{p}_t = 0$, and from (8) $h_t = h* \Rightarrow \dot{h}_t = 0,$ the system reaches a steady state at the price, c^b, and the aquifer head level, $h*$.

The solution to the optimal control problem is governed by the system of differential equations:

(9) $$\dot{h}_t = w - l(h_t) - q_t$$

(10) $$\dot{p}_t = (r + l'(h_t))(p_t - c(h_t)) + (w - l(h_t))c'(h_t)$$

where equation (9) is the same as equation (1), and equation (10) results from combining equations (1), (2), and (5) and the time derivative of (5) by eliminating $\lambda_t, \dot{\lambda}_t$, and $\dot{h}_t$

Using the Pearl Harbor aquifer information, we calculate the optimal extraction rates and price paths. The solution method is to fist use equation (8) to calculate the final head, h^*, and then solve for the end time, t_f such that the solution to the system of differential equations (9) and (10) with boundary conditions $h(t_f) = h^*$ and $p(t_f) = \overline{p}$ results in $h(t_0) = h_0$.

For Case 2: watershed degradation as an uncertain event, we assume the time at which the adverse watershed event can occur is at the end of 20 years from now. We then divide the time horizon into two stages. Stage 1 is the period of first 20 years (before the adverse event can occur) and stage 2 is the period afterwards. Stage 2 has two cases: a) adverse watershed event does not occur with the probability of 90% and aquifer recharge does not decrease; b) the one-time event does occur with the probability of 10% and aquifer recharge decreases by 31 %.

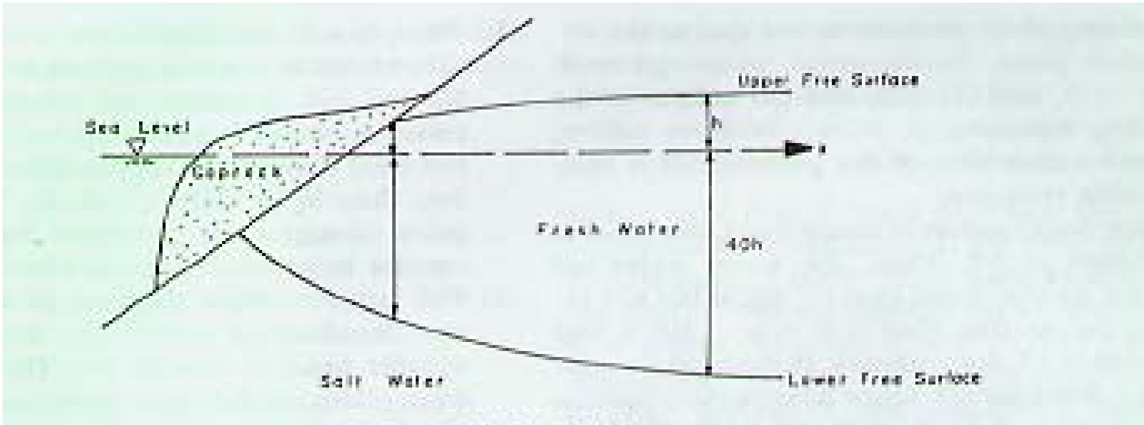
We apply similar procedure to the certainty case to derive the optimal price and cost paths. We first solve stage 2 and then stage 1. For stage 2, the boundary conditions are the backstop price and the beginning head level. The backstop price is desalination cost as measured in the certainty case. The beginning head level for stage 2 is equal to the ending head level for stage 1.

For stage 1, we obtain the price and head paths by following the corresponding equations of motion, starting from the current head level and an appropriately chosen beginning price such that the price at the end of stage 1 is equal to the probability weighted average of the beginning prices of the two cases of stage 2

3. Application

3.1 Description

According to Mink (1980), most coastal aquifers in Hawai'i exhibit some form of a basal or Ghyben-Herzberg lens (see figure below). This is the result of less-dense freshwater floating on the denser seawater as it makes its way from inland to the sea and discharges into the ocean. The volume of water stored in the aquifer is a direct function of head but also depends on the aquifers boundaries, lens geometry, and aquifer porosity (Mink 1980). The upper and lower surfaces of the aquifers are nearly flat. Thus, volume of aquifer storage is modeled as linearly related to head level.



Source: Mink (1980)

Following Krulce et. al. (1997), using aquifer dimensions and effective rock porosity of 10%, Pearl Harbor aquifer has 78.149 billion gallons of water stored per foot of head. This value is used to calculate a conversion factor from head level in feet to volume in billion gallons. Extracting 1 billion gallons of water from the aquifer would lower the head by 1/78 or 0.012796 feet.

The natural inflow to the aquifer is on average 281 million gallons per day (mgd). Leakage from the aquifer is quadratically related to head as $l(h) = 0.24972h^2 + 0.022023h$, where *l(h)* is measured in mgd. The maximum head level, obtained when no water is extracted from the aquifer and recharge rate and leakage are in balance, can be calculated by solving $w = l(h)$, which gives $\overline{h} = 33.5$ feet. Since head level can never exceed this maximum value or be negative, *l(h)* is restricted to the domain (0, 33.5) over which $l' > 0, l'' > 0$.

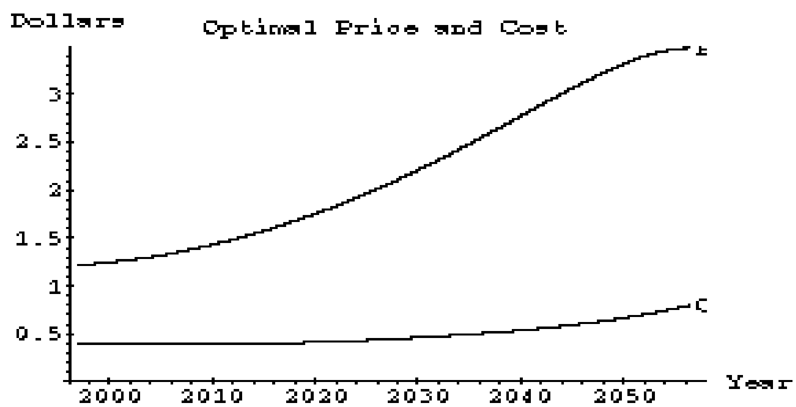
Demand is modeled with a constant elasticity demand function that grows over time at a constant rate. Thus, $D(p,t) = \alpha e^{gt}(p_t + c_D)^{-\eta}$, where g is the growth rate of demand equals to the income and population growth rate of island, p_t is the wholesale price of water, c_D is the distribution cost, and η is the elasticity of demand. The growth rate of demand equals to 1%. Retail price is set at \$1.77 per thousand gallons, this gives α = 221.35, with demand measured in mgd and price in dollars per thousand gallons. The 1997 retail price of water is \$1.77 per thousand gallons and the 1997 pumping costs is \$0.407 per thousand gallons. Thus, c_D = \$1.363. Unit cost of desalination is \$3.48 per thousand gallons. Discount rate is 3%.

3.2. Results

1. Watershed Degradation Certain and Soon

The deterioration of watershed quality anticipated in this paper is a decrease in groundwater recharge of 41 mgd, or 31% of the current recharge level from the Ko'olaus. Optimal price and extraction cost trajectories are given in Figure 1. The steady state is reached in the year 2052, much sooner that the case of efficiency with conservation spending. Hence, the benefit of watershed conservation is the delay in the investment in desalination and desalination facility. Table 1 and Table 2 provide evaluated net welfare losses due to watershed degradation.

Figure 1: Optimal price and extraction cost with recharge reduction of 41 MGD



Source: Kaiser and Roumasset (2002).

Table 1: Sensitivity Analysis of Present Value Social Losses, different reduced recharge and discount rates

Estimates of Present Value Social Losses from Deterioration in Forest Quality, in Billions of Dollars.		
Change in Forest Recharge:	Discount rate = 3%	Discount rate = 1%
Base: 41MGD (31%)	1.1329	2.3187
15 MGD: lower than expected loss (-11%)	0.4205	0.9569
30 MGD: lower than expected loss (-23%)	0.8389	1.7867
39 MGD: (-29%)	1.0898	2.2674
43 MGD: (-32%)	1.2107	2.4948

Table 2: Sensitivity Analysis of Present Value Social Losses, different extraction costs and demand growth rates

Estimates of Present Value Social Losses from Deterioration in Forest Quality of 31% (41 MGD) in Billions of Dollars			
	Discount Rate = 3%		Discount Rate = 1%
Extraction cost:	1% demand growth	2% demand growth	1% demand growth
Slow rising (n=1)	1.1074	0.7781	2.4131
Medium rising (n=2)	1.1329	0.8030	2.3187
Fast rising (n=4)	1.3736	0.8503	2.3666

2. Watershed Degradation as An Uncertain Future Event

An adverse event is assumed to occur or not after 20 years. The severity of the event is 30% damage. The probability of occurrence is 10%. The optimal price and cost paths are separated into two stages -- before and after the adverse event may occur. The social planner maximizes the expected benefits of water consumption. The results for each scenario are presented in Figure 2. The corresponding optimal head level is provided in Figure 3. Extraction cost remains relatively stable through out the time of the study. Therefore, the change in scarcity rent, the difference between price of water and extraction cost, is determined by the change in the price level.

Both graphs exhibit the diversion in price and head level trajectories at the beginning of the second stage. If the event occurs, there has been overuse (ex post), and the efficiency price suddenly jumps higher, reflecting increased scarcity. If the event does not occur, the efficiency price decreases only slightly, inasmuch as this event was expected with 90% probability. Correspondingly, Figure 3 shows that the head level decreases more rapidly if the event occurs. With unexpected drawdown, the aquifer is depleted much faster.

Specifically, when there is no adverse event, price drops by 10% before continuing its increasing trend. The magnitude of the initial drop in price is one-ninth of the increase in the with-event case, corresponding to the 90% probability of no-adverse event. Population growth, income growth, and diminishing water resource contribute to the rising price pattern in the later years. Figure 3 shows a slower decrease in the optimal head level trajectory for the no-event case. Watershed conservation can extend the life of groundwater resource and prolong the needs for substitute technology for 20 years. The resulting savings in welfare are reported in Table 3.

Figure 2: Optimal price paths without conservation

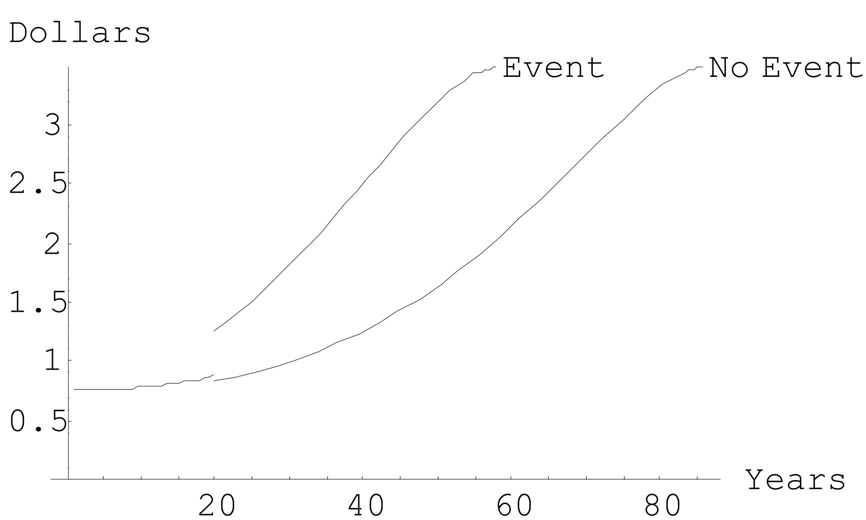


Figure 3: Optimal Head Level

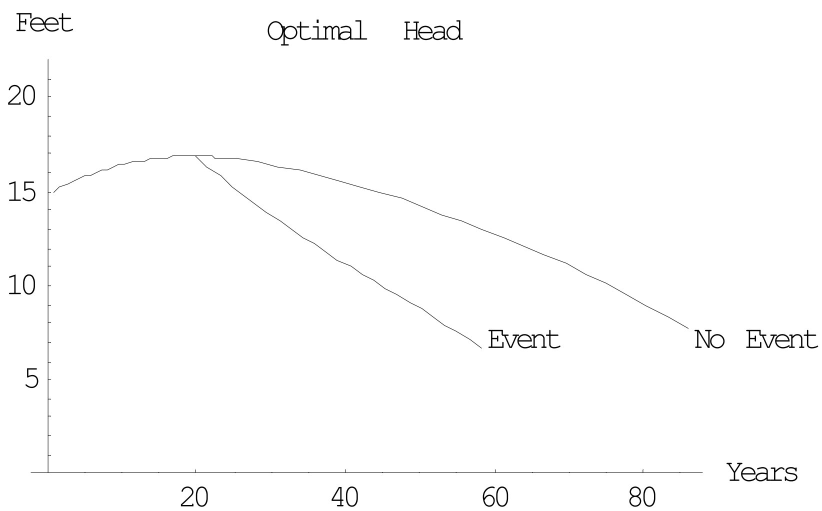


Table 3: Present Value of Loss in Welfare ($ million)		
Recharge loss happens (Probability 10 %)	Recharge loss does not happen (Probability 90 %)	Expected Value
975	0	97.5

4. Conclusion

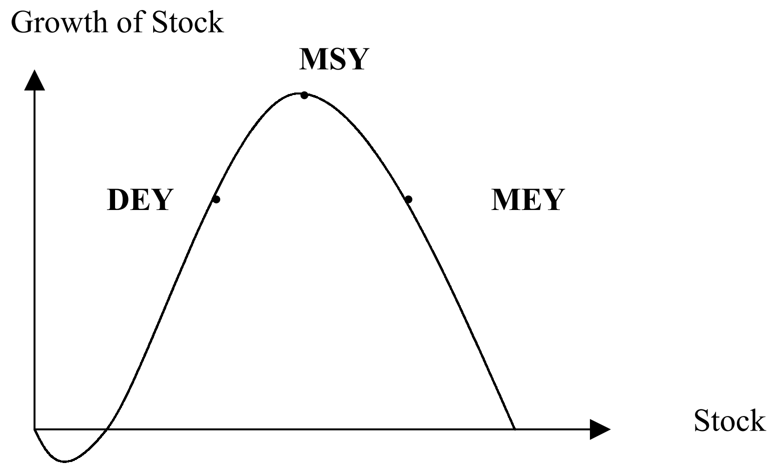
To begin, we examined the value of conservation, assuming that watershed degradation is certain and soon in the absence of conservation. If 31% of recharge is lost, the present value of the aquifer decreases by more than $1.1 billion, assuming a 3% social discount rate and efficient resource utilitization. Under this scenario desalination must be employed 20 years earlier than with conservation. Sensitivity analysis is performed for changes in the discount rate, recharge loss, extraction costs for water, and different rates of growth in demand.

In contrast, the second case provides a model wherein the unconserved resource is subject to a risk of degradation. Assuming a very modest probability of 10% that the resource is degraded by 30% after 20 years, we find that the expected benefits of conservation are almost $97.5 million while the costs of conservation are only $15 million. This estimate assumes that the resource manager optimally solves the problem of water extraction under uncertainty and knows that the optimal price path is discontinuous and jumps up or down after the event or non-event is realized. In the likely event of mismanagement, inasmuch as water managers are typically unfamiliar with economic optimization even under certainty, the gains of conservation will be larger. Even in this case, conservation combined with efficient water management is a win-win-win for consumers, taxpayers, and the environment, albeit in the sense that the environmental insurance acquired through conservation costs less than its expected value. However, if conservation is done without improving water management, the benefits are likely to be less than the costs.

Appendix 1
Alternative definitions of sustainable yield in resource economics

There are several definitions of sustainable yield. In general, s*ustainable yield (SY)* is the path of natural resource use that leads to constant consumption into the indefinite future. Figure 6 shows the growth of stock as the function of stock itself. In the positive quadrant, increase in stock initially raises the growth rate. Later, the process reverses: large population leads to a decline in the growth of stock.

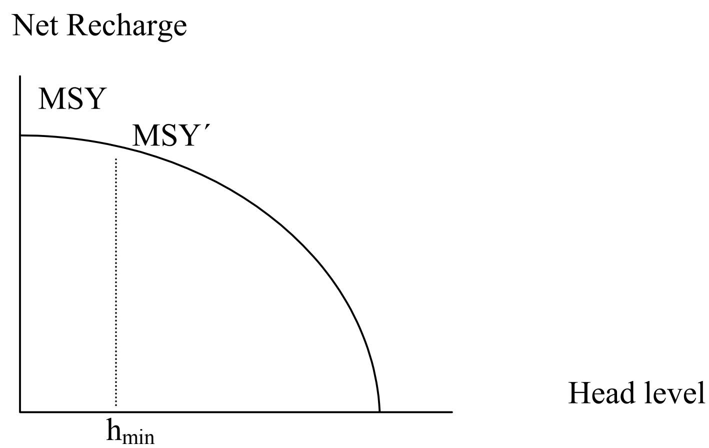
Figure 6: Resource Growth Function



Some well-known concepts of sustainable yield are presented: *Maximum Sustainable Yield (MSY)* is the sustainable yield that maximizes the biomass of the resource. *Maximum Economic Yield (MEY)* is the sustainable that maximize present value of net benefits of resource consumption. Recognizing the benefits of intergeneration transfer, *Dynamic Economic Yield (DEY)* is the sustainable yield which maximize the present value of the dynamic net benefits. Arbitrage condition equalizes the benefit from waiting and the cost of resource extraction. In practice, however, any point on the positive quadrant of the curve can represent *sustainable yield*. By harvesting the resource at the rate equals to the growth rate of the population, the stock of resource remains constant and sustainable yield is achieved.

For the case of groundwater resource, an aquifer is considered a renewable but exhaustible resource. The aquifer is recharged through percolation of rainwater and depleted when water leaks from the basin to the sea and when water extraction occurs. The current head level affects the amount of water leakage and extraction cost. The lower the head level, the more expensive the extraction costs becomes. Therefore, there is a lower limit to the head level, h_{min}, in which further extraction will deplete the aquifer condition beyond the replaceable level. Without the head level constraint, maximum sustainable yield (MSY) equals to the constant recharge rate. Imposing the minimum head level constraint, i.e. the head level of the aquifer before the aquifer goes saline, MSY will be at the growth rate where the head level equals to the minimum head level. The net recharge and the head level information are presented in Figure 7.

Figure 7: Aquifer Net Recharge Function



The level of h_{min} has been chosen using different criteria such as 1) h_{min} is the level that structure of the well will be destroyed, 2) h_{min} represents the level in which the well will turn saline, or 3) h_{min} is an arbitrary level chosen by the Board of Water Supply.

Similar to Figure 6, any head level maintained at the level greater than h_{min} is sustainable. h_{min} may or may not be DEY. The arbitrage condition might result in water extraction that never drives down the head level to h_{min} and provide constant water usage indefinitely.

Appendix 2
Determining the watershed quality: recharge connection

A survey of differentiated experts on forest quality and groundwater recharge, from the USGS, DLNR, USFS (Pacific Islands Forestry Institute) and UHManoa, indicated the following general characteristics:

1) The Koolau watershed is fairly healthy for the purposes of watershed today.

2) The 20 year forecast for change in that quality indicates some possibility of change, with answers ranging from 0% chance of deterioration to 40% chance of deterioration in forest quality for watershed purposes. We settle on 10% as it is within the acceptable range of potential change for all survey participants.

3) The mechanisms for change are uncertain. The table below describes each respondent's greatest perceived threats:

Respondents	**Threats to watershed quality**
Respondent 1	Vehicular access
Respondent 2	Ecotourism (access), human intervention, politics
Respondent 3	Pigs, invasives (Miconia)
Respondent 4	Weedy species, pigs
Respondent 5	Miconia, pigs, goats
Respondent 6	Noxious weeds, fire

4) Though we assume conservation activities correspond to certain alleviation of the threat, conservation activities will differ in cost-effectiveness. To establish the anticipated costs of forestalling the forest damages, we asked participants to name the most cost-effective conservation activities. These are presented in the table below:

Respondents	**Cost-effective conservation activities**
Respondent 1	Elimination of off road 4X4 vehicles (military too)
Respondent 2	Control political discussions about entry
Respondent 3	Increased number of stream gauges; hunting (pig control); monitoring and information gathering on soil moisture and erosion
Respondent 4	Fencing
Respondent 5	Fencing; replanting eroded areas; hunting
Respondent 6	Early detection/rapid response for weeds; access for hunting; water & management monitoring

5). The 41 MGD anticipated decrease in recharge was determined again by questioning the experts on the meaning of a significant disturbance in recharge that would accompany a change from healthy forested watershed to a landscape transformed by a combination of invasive plant and animal interactions, which currently threaten the islands of Hawaii. The figure of approximately 1/3 of the recharge from the Ko'olau conservation district portion of the aquifer (133 MGD) emerged as a feasible, likely outcome.

References

Dasgupta, Partha, and Geoffrey Heal (1979). *Economic Theory and Exhaustible Resources*, Cambridge University Press, Nisbet, Cambridge.

Dasgupta, Partha, and Joseph Stiglitz (1981). "Resource Depletion Under Technical Uncertainty," *Econometrica*, Vol. 49, No. 1. (Jan., 1981), pp. 85-104.

Krulce, Darrel, James Roumasset, and Tom Wilson (1998). "Optimal Management of a Renewable and Replaceable Resource: The Case of Coastal Groundwater," *Journal of Agricultural Economics*, Vol. 79. pp. 1218-1228.

Kaiser, Brooks, Nancy Krause, Dee Mecham, James Roumasset (1998). "Environmental Valuation and the Hawaiian Economy," University of Hawaii Economic Research Organization, Working Paper (http://www2.hawaii.edu/~uhero/).

Kaiser, Brooks, and James Roumasset (2000). "Valuing Indirect Ecosystem Services: the Case of Tropical Watersheds," *Journal of Environmental and Development Economics*, Vol. 7, Part 4. (Oct., 2002), pp.701-714.

Kaiser, Brooks, and James Roumasset (2000). "Water Management and the Valuation of Indirect Environmental Services", *Interdisciplinary Environmental Review*, v. II, n. 2

Loury, Glenn (1978). "The Optimal Extraction of an Unknown Resource," *The Review of Economic Studies*, Vol. 45, No. 3. (Oct., 1978), pp. 621-636.

Mink, J (1980). *State of the Groundwater resources of Southern Oahu.* Board of Water Supply, Honolulu.

Moncur, James, Rodney Smith, James Roumasset, Just Netanyahu (1998). "Optimal Allocation of Ground and Surface Water in Oahu: Water Wars in Paradise," *Conflict and Cooperation in Water Management*, Kluwer Academic Publishers.

Pindyck, Robert (1984). "Uncertainty in the Theory of Renewable Resource Markets," *The Review of Economic Studies*, Vol. 51, No. 2. (Apr., 1984), pp. 289-303.

Smith, Rodney, and James Roumasset (2000). "Constrained Conjunctive Use for Endogenously Separable Water Markets: Managing the Waihole-Waikane Aqueduct," *Journal of Agricultural Economics,* 1487, pp. 1-11.

Tsur, Yacov, and Amos Zemel (2002). "Endangered Aquifers: Groundwater Management Under Threats of Catastrophic Events," Discussion Paper No. 9.02, Department of Agricultural Economics and Management, The Hebrew University of Jerusalem, November 2002.

Roumasset, James, and Rodney Smith (2001). "Inter-district Water Allocation with Conjunctive Use," *Water Resources Update*, January, 2001.